Calibration on the Fly—A Novel Two-port S-Parameter Measurement Method for On-wafer Leaky Systems

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***Abstract*—In this paper, we present a two-port on-wafer scattering parameter measurement method to tackle the issue of crosstalk between probes. The proposed method treats the crosstalk separately during the system calibration and the device measurement stages, because the crosstalk during these stages is often different due to changes in the measurement conditions after the probes have been calibrated. For example, devices under test (DUTs) and calibration standards are often situated on different substrates, or, the distance between probes during calibration is different from that during DUT measurement. Based on this concept, we develop a new error model in which the crosstalk is treated as a standalone two-port error network in parallel with the two-port calibration standards or DUTs. The two-port crosstalk error generated during probing, E_{CT}, is removed in the system calibration and corrected during the measurement of the DUT by using a dummy pair of open-circuit standards that are fabricated on the same substrate as the DUT. Since the crosstalk is corrected while measuring the DUT, rather than during system calibration, we call this method "calibration on the fly" (COF). The method is demonstrated using measurements of a 10-dB attenuator between 140 GHz and 220 GHz.**

***Index Terms*—Millimeter-wave measurement, on-wafer measurement, calibration, scattering parameter, error model.**

I. Introduction

Over the past 30 years, system error models for scattering parameter (S-parameter) measurement have been developed and implemented in coaxial, waveguide, and on-wafer measurement systems. The most widely used calibration methods, such as short-open-load-thru (SOLT) [1], thru-reflect-line (TRL) [2] and line-reflect-match (LRM) [3], are based on either 8-term or 12-term error models and do not contain corrections for crosstalk, because it is either non-existent or negligibly small.

For on-wafer measurements, the limitations in using the conventional error models become significant at high frequencies e.g., 100 GHz and above. This is mainly due to the nonnegligible crosstalk or leakage generated when probes are brought closer together in order to reduce system losses at these frequencies. The fringing effect between the probes leads to a leakage path from one probe to the other when the probes are in close proximity with each other. This is the case when testing components and transistors in monolithic millimeter wave integrated circuits.

The presence of crosstalk in S-parameter measurements is a well-documented problem. To address the probe-to-probe coupling issue, Speciale [4] introduced a 16-term error model, as shown in Fig. 1. The eight conventional error terms (plotted with solid lines in Fig. 1) and eight crosstalk error terms (plotted with dotted lines) are treated as a four-port network in cascade between the vector network analyzer (VNA) and the device under test (DUT). The 16 errors can be solved by using at least five two-port standards whose S-parameters are fully known, and at least one of them is asymmetric (e.g., an

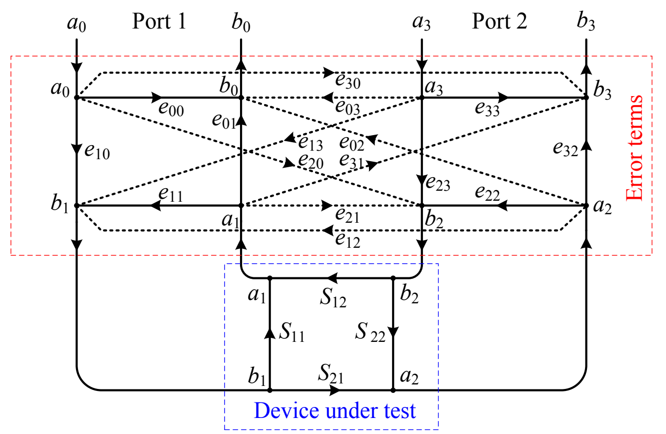

Fig. 1. The 16-term error model introduced by Speciale [4]. The solid lines represent the actual signal transmission and reflection paths; the dotted lines represent the leakages or crosstalk.

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open-load pair [5], [6]). Since then, several developments have been proposed to improve and optimize the original 16-term error model.

In 1997, Silvonen [7] developed a thru-match-reflect/ line-match-reflect (TMR/LMR) self-calibration method which reduces the number of calibration standards and therefore simplifies the calibration procedure. In 2012, a short-open-load-reciprocal (SOLR) calibration method for multi-port on-wafer measurement was introduced [8]. Subsequently, a method enabling the calibration of the full 16-term errors was developed using only four calibration standards [9]. In 2014, Dahlberg *et al*. [10] proposed to define the calibration standards for the line-reflect-reflect-match (LRRM) method in a reciprocal 16-term error network. More recently, Williams *et al*. [11] used the 16-term error model as a second-tier calibration to determine the crosstalk error terms (plotted with dotted lines in Fig. 1) provided that the other eight error terms had been solved by a multiline-TRL calibration [12], [13]. In 2018, Liu *et al.* [14] showed that two leakage paths i.e., e_{21} and e_{12}, actually represent the probe-to-probe crosstalk, and the other six error terms are negligibly small and so can be ignored. In all previous cases, the crosstalk generated between probe tips i.e., e_{21} and e_{12}, is always treated as a constant. However, this is generally not the case. In practice, the crosstalk changes as probe separation changes, especially at high frequencies.

To tackle this problem, we propose a new error model to represent the system errors in a modern two-port on-wafer S-parameter measurement system. The varying probe-to-probe crosstalk is considered as a standalone two-port error network in parallel with any two-port standard or DUT. Since the crosstalk generated during system calibration and device measurement stages is different, it is treated separately. We first remove the crosstalk error in the system calibration and then correct the crosstalk generated during the device measurement stage. We therefore call this method "calibration on the fly" (COF).

In addition, we will limit our study to coplanar waveguide (CPW) with ground-signal-ground topology in this paper. Other topologies such as leakage in multimode waveguides for multiport or differential measurements [15], [16] are beyond the scope of this work.

II. Probe-to-probe Crosstalk

In Speciale's 16-term error model [4], crosstalk is treated as a constant and corrected during system calibration. However, the crosstalk often changes as the measurement environment changes whether it is for off-chip calibration, where DUTs and calibration standards are on different substrates, or for on-chip calibration where DUTs and calibration standards are on the same substrate. For the former, different substrates have different dielectric properties therefore different coupling; for the latter, the distance between probes during calibration is often different from that during the measurement of the DUTs. This also applies to the off-chip calibration scenario. To demonstrate how crosstalk is affected by the conditions of the measurement, we undertook the two experiments described below.

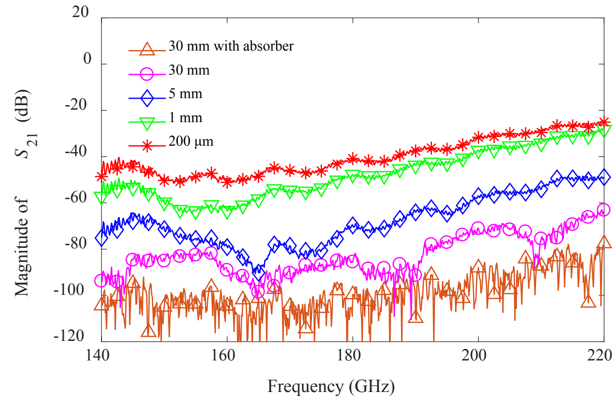


Fig. 2. Measured uncorrected raw data of $|S_{21}|$ for different separations between probes while probe tips are in the air. Probe separation has a large impact on crosstalk [14].

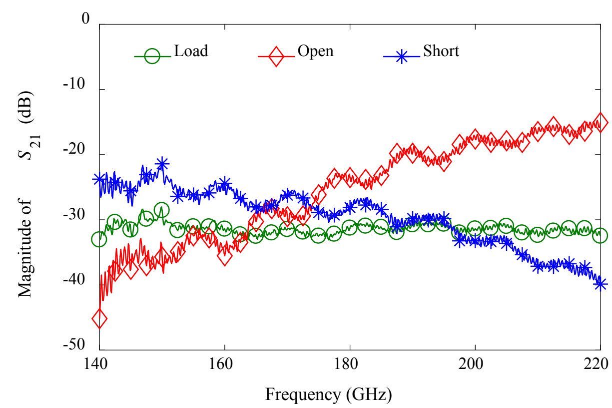


Fig. 3. Measured uncorrected raw data of $|S_{21}|$ for DUTs with the same separation and different reflection. The reflection has a large impact on crosstalk.

In the first experiment, we measured raw (uncorrected) forward transmission coefficients (S_{21}), which represents the crosstalk, between two G-band (140 GHz to 220 GHz) probes when placed in air and separated by various distances. As shown in Fig. 2, $|S_{21}|$ is close to -20 dB at 220 GHz when the probes were separated by 200 μm and decreases as the distance between the probes increases. When the two probes are separated by 30 mm, the coupling is as low as -80 dB, and even -100 dB when a microwave absorber (Cascade PN 116-344) is inserted between the probes. From this experiment, we conclude that the crosstalk varies greatly with the distance between probes.

In another experiment we investigated how probe-to-probe crosstalk is influenced by the type of DUT being measured. To do this, we measured three pairs of standards – open-open, short-short, and load-load – on a commercial CS-15 impedance standard substrate (ISS) from GGB Industries, Inc. Each pair has the same separation distance i.e., 150 μm. The measured $|S_{21}|$ is plotted in Fig. 3. From these results, we can see that the crosstalk changes with both frequency and the type of DUT. The reflection coefficient of the DUTs has a significant influence on the crosstalk. Therefore, we conclude that it is

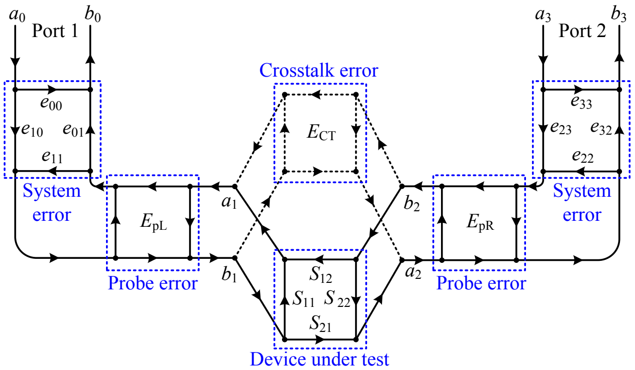


Fig. 4. The proposed new error model described in this paper. The crosstalk errors (plotted with dotted lines) are treated as a two-port network in parallel with DUT.

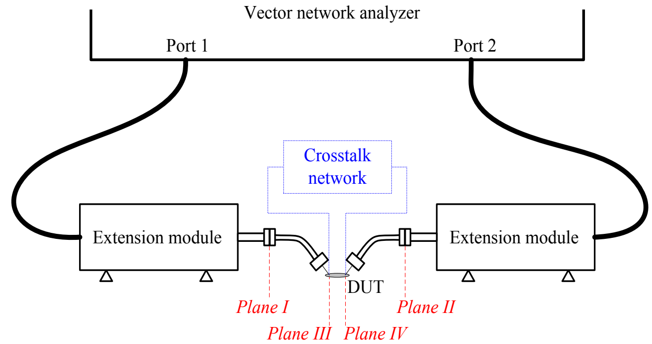


Fig. 5. Block diagram for full two-port S-parameters on-wafer measurement systems. The reference plane for each waveguide port is marked as *Plane I* and *Plane II*, respectively, and the reference plane for each probe tip is marked as *Plane III* and *Plane IV*, respectively.

inappropriate to treat crosstalk for calibration and measurement as a constant.

To truly represent the crosstalk, we propose a new error model. As shown in Fig. 4, the probe-to-probe crosstalk is treated as a standalone two-port error network in parallel with the DUT during measurement. The crosstalk error, generated when probing, is removed during the system calibration and characterized using a dummy open-open pair that are fabricated on the same substrate as the DUTs. Then the crosstalk can be removed from the DUT measurements.

III. The Proposed Error Model

As discussed in the previous section, crosstalk exists between probes in a two-port on-wafer S-parameter measurement system due to signals leaking from one probe tip to the other both in the substrate and in the air. The crosstalk varies depending on the loads being probed. We treat the crosstalk as a "virtual two-port network" (e.g., as an attenuator with high attenuation and high impedance) which is in parallel with a DUT during measurement, or a pair of standards during calibration. As shown in Fig. 4, all errors in the error model can be decomposed into three types: system errors, probe errors and crosstalk errors. This assumption is based on a modern VNA which has very low internal leakages [17]. The S-parameters of the "virtual network" are marked as $E_{CT,\,ij}$, where $i, j = 1$ or 2, separately. If there is no crosstalk, the "virtual network" can be treated as an ideal pair of ideal open standards i.e., $E_{CT,\,11} = E_{CT,\,22} = 1$, and $E_{CT,\,21} = E_{CT,\,12} = 0$. In this case, this error model becomes the conventional 8-term error model which is widely used in TRL and LRM calibration methods for coaxial and rectangular waveguides.

To apply this error model to a real on-wafer S-parameter calibration, we need to separate the crosstalk, or the "virtual network", from the DUT. Fig. 5 illustrates a possible implementation of the new technique at frequencies from 140 GHz to 220 GHz (G-band). We define the reference planes at each waveguide port as *Plane I* and *Plane II*, respectively, and the reference planes at the probe tips as *Plane III* and *Plane IV*, respectively.

Like a two-tier calibration, the correction procedure requires two calibrations. The first calibration is a waveguide calibration, which is performed at *Plane I* and *Plane II*. Since there is no crosstalk between two waveguide ports, a standard SOLT calibration in waveguide can be implemented. The second calibration, i.e., probe calibration, is performed at *Plane III* and *Plane IV*, which are probe tips to remove probe errors, therefore an ISS is used. To characterize the crosstalk generated when measuring DUTs, an open-open pair on the same wafer as the DUTs and having the same physical length as the DUTs is required. A detailed calibration procedure, showing how the errors in the new model are solved, is described below.

A. Waveguide Calibration

A VNA is first calibrated as its waveguide ports (i.e., *Plane I* and *Plane II* in Fig. 5) using the conventional two-port SOLT method with waveguide standards. This calibration solves the eight system error terms, i.e., e_{00}, e_{10}, e_{01}, e_{11}, e_{33}, e_{23}, e_{32} and e_{22}, as shown in Fig. 4.

B. On-wafer Calibration

After the two-port waveguide calibration, probes are installed and one-port SOL calibration is performed at the probe tips (i.e., *Plane III* and *Plane IV* in Fig. 5) individually using a commercial ISS (e.g., CS-15 from GGB Inc.) to extract the S-parameters or probe error terms of the left probe, E_{pL}, and the right probe, E_{pR}. This extraction can be achieved using the built-in programme "AdaptorChar Marco" in a Keysight PNA-X VNA (all of the major VNA vendors have a similar Bauer-Penfield utility [18]). We used the models provided by the vendor for the SOL standards. More accurate models e.g., based on full-wave simulation of SOL standards [19]-[20] can be used for the extraction. In addition, the SOL method can be replaced with an over-determined set of offset shorts for probe characterization [21]. Note when performing one-port SOL calibration on one probe, the other probe should be separated by at least 30 mm to avoid probe-to-probe crosstalk. Once the S-parameters of the two probes have been obtained, the reference planes can be moved from *Planes I* and *II* to *Planes III* and *IV* using de-embedding techniques. Details about this de-embedding process are given in the next sub-section.

In fact, Steps *A* and *B* can be combined using an on-wafer

SOLR calibration method which requires an additional thru.

C. Crosstalk Characterization

The crosstalk errors are corrected with a dummy open-open pair with the same physical length as the DUT fabricated on the same wafer. This is because open standards, as shown in Fig. 3, have increased crosstalk as the frequency increases and are believed to be the main source of the coupling between probes. If the open-open pair standard is ideal i.e., $|S_{11}| = |S_{22}| = 1$, and $|S_{21}| = |S_{12}| = 0$, the measured S-parameters are the cascaded S-parameters of the left probe, crosstalk network, and the right probe. In reality, the open-open pair is nonideal and so its S-parameters (S_{open}) can be defined using [22]. Based on the waveguide calibration, the measured S-parameters (S_{M}) are the cascaded S-parameters of the left probe, the crosstalk network in parallel with the open-open pair standard, and the right probe.

T-parameters are used to de-embed the left probe and the right probe from S_{M} [23]. The S-parameters of the open-open pair in parallel with the crosstalk network ($S_{\text{open}||\text{CT}}$) can then be obtained. (Here the "||" sign means "in parallel".)

Converting S-parameters to Y-parameters, and then using (1) to separate S_{open} from $S_{\text{open}||\text{CT}}$, we can obtain E_{CT} from Y_{CT}.

$$Y_{\text{CT}} = Y_{\text{open}||\text{CT}} - Y_{\text{open}} \tag{1}$$

The relationship between S-parameters and Y-parameters is given in (2) and (3) [23], where

$$\Delta_Y S = \left(1+S_{11}\right)\left(1+S_{22}\right) - S_{21}S_{12} \tag{4}$$

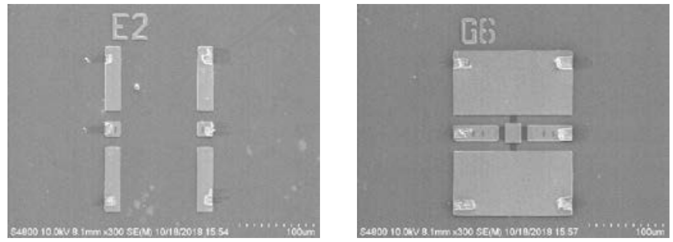
$$\Delta Y = \left(Y_0+Y_{11}\right)\left(Y_0+Y_{22}\right) - Y_{21}Y_{12} \tag{5}$$

where Y_0 is the system admittance (i.e., the inverse of the system impedance, Z_0).

We also investigated short-short and load-load pair standards at lower frequencies i.e., below 50 GHz, and found that the load-load pair standard has similar effect as the open-open pair standard; however, the short-short pair standard is not feasible due to a singularity generated in (1). The singularity could perhaps be mitigated using a mathematical means.

D. DUT Test

Also, based on the waveguide calibration, the S-parameters obtained between *Plane I* and *Plane II* for a DUT are labelled as S_{m}. Again, using T-parameters to de-embed E_{pL} and E_{pR} from S_{m}, the S-parameters of the DUT in parallel with the crosstalk network ($S_{\text{DUT}||\text{CT}}$) can be obtained. Then, using Y-parameters to separate the crosstalk network from $S_{\text{DUT}||\text{CT}}$ in (6), the S-parameters of the DUT are obtained from Y_{DUT}.



(a) (b)

Fig. 6. SEM image of the open-open pair standard (a) and the attenuator (b). The open-open pair standard and the attenuator were fabricated on the same 4-inch semi-insulating gallium arsenide substrate using a standard photolithography method.

TABLE I
SYSTEM CONFIGURATION

System Configuration	Model & Manufacturer / Parameters
VNA	PNA-X N5247A, Keysight
Frequency Extenders	WR-05, VDI
Probe station	Customized Cascade (manual)
Probes	220-GSG-75-BT-M, GGB
No. of frequency points	801
IF bandwidth	100 Hz

$$Y_{\text{DUT}} = Y_{\text{DUT}||\text{CT}} - Y_{\text{CT}} \tag{6}$$

When measuring other DUTs of different lengths, the crosstalk network will change and will need to be re-characterized. In this case, a corresponding open-open pair with the same length as the new DUT is required and the same crosstalk characterization procedure described in sub-section C, above, should be implemented for the actual S-parameters of the new DUT.

According to the above method, the crosstalk error is removed while measuring the DUT rather than during the system calibration - hence, this method is called "calibration on the fly" (COF).

IV. EXPERIMENTAL RESULTS

To evaluate the COF method, a 10-dB attenuator was designed with the aid of commercial software (i.e., CST Microwave Studio) and fabricated on a 600-μm thick semi-insulating gallium arsenide substrate using standard photolithography technology. A 400-nm layer of gold was deposited for the conductors and a thin layer of nickel-chrome alloy was used for the resistors. A two-port open-open pair was also fabricated on the same substrate. The spacing between circuits was kept to a minimum of $3\lambda_g$, which is greater than that suggested in [24]. The substrate was then thinned down to 100

$$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} = \frac{Y_0}{\Delta_Y S}\begin{bmatrix} \left(1-S_{11}\right)\left(1+S_{22}\right)+S_{21}S_{12} & -2S_{12} \\ -2S_{21} & \left(1+S_{11}\right)\left(1-S_{22}\right)+S_{21}S_{12} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{\Delta Y}\begin{bmatrix} \left(Y_0-Y_{11}\right)\left(Y_0+Y_{22}\right)+Y_{21}Y_{12} & -2Y_{12}Y_0 \\ -2Y_{21}Y_0 & \left(Y_0+Y_{11}\right)\left(Y_0-Y_{22}\right)+Y_{21}Y_{12} \end{bmatrix} \tag{3}$$

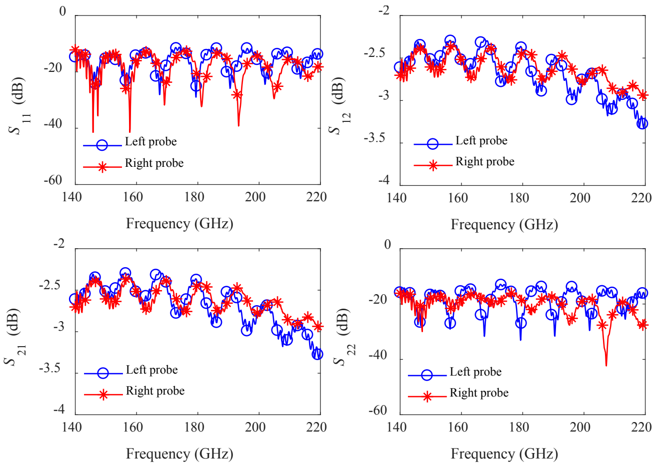


Fig. 7. S-parameters of the probes. Ports 1 and 2 are the waveguide port and probe tip, respectively.

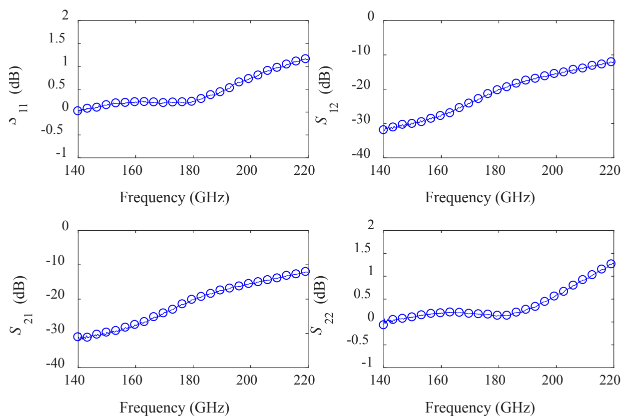


Fig. 8. S-parameters of the crosstalk network.

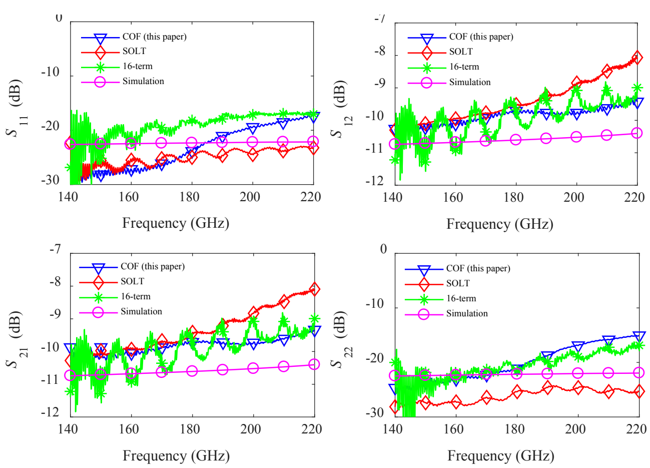


Fig. 9. Comparisons of S-parameters of a 10-dB attenuator corrected using the COF method (described in this paper), 16-term error model based on SVD method [6], SOLT (conventional 12-term error model), along with the simulated results.

μm after all circuits were made.

Fig. 6 shows a scanning electron microscope (SEM) image of the fabricated attenuator. All aforementioned components have the same edge-to-edge distance (i.e., 160 μm) in order to keep the distance constant during calibration and measurement. We defined the offset of the standards with reference to [22]. A G-band (i.e., 140 GHz to 220 GHz) on-wafer S-parameter measurement setup, including a manual probe station, at the National Physical Laboratory (NPL), U.K. and two probes from GGB Industries, Inc., was used for the measurements. The system configuration is shown in Table I.

Fig. 7 shows the extracted S-parameters of the probes. Port 1 and Port 2 refer to the waveguide port and probe tip of the probes, respectively. Fig. 8 shows extracted S-parameters of the crosstalk network (S_{CT}) using the above-mentioned calibration procedure. As shown in this figure, the transmission coefficients (i.e., $|S_{21}|$ and $|S_{12}|$) are approximately –30 dB at 140 GHz, increasing to close to –10 dB when the frequency reaches 220 GHz. Port reflections (i.e., $|S_{11}|$ and $|S_{22}|$) are greater than 0 dB. This may result from probe launch differences between calibration and measurement [25]-[27].

Fig. 9 shows S-parameters of the 10-dB attenuator, corrected using the COF method, 16-term error model based on SVD method [6], and the standard on-wafer SOLT calibration method, along with simulated S-parameters using CST Microwave Studio. It is clear that the magnitudes of S_{21} and S_{12} corrected by the COF method show better agreement with the simulation results compared with the results corrected using the SOLT method, particularly at the higher frequencies in the band (i.e., above 180 GHz) where the presence of crosstalk is more likely to be a problem. The main reason for this is that the conventional 12-term error based SOLT calibration technique does not correct for the effect of crosstalk properly; therefore, the crosstalk contributes to the total observed transmission between the probes.

It is also observed that the S-parameters corrected using COF method is free of ripples comparing with those corrected using the 16-term error model. In the authors' opinion, the ripples shown in the 16-term error model are likely due to two reasons: one is that the 16-term error model treats the probe-to-probe crosstalk as a constant, but in fact it varies with the length and impedance of the DUT, as described in Section II; the other is that the 16-term error model requires five standards whose S-parameters are fully known, but in practice four standards along with SVD method are used which leads to approximation.

In addition, one may notice that the inconsistent of return loss shown in Fig. 9. In the authors' opinion, the difference in reflection may be caused by the inconsistent broadband matched standards between the chip and the rectangular waveguide. The reflection is heavily dependent on the load standard in SOLT calibration. However, it is difficult to manufacture broadband matched loads very accurately for rectangular waveguides or on-chip.

V. Conclusion

In this paper, we have presented a new error model for a two-port on-wafer measurement system. The new model truly reflects the variable probe-to-probe crosstalk that is subject to change during the calibration/measurement process. The new error model separates the probe errors from the system errors and treats the probe-to-probe crosstalk as an error network in parallel with the DUT. Thus, the crosstalk can be corrected while measuring the DUT. Based on the new error model, a novel COF calibration and measurement method has been presented. To implement this method, an open-open pair standard fabricated on the same substrate as the DUT was used for crosstalk correction. A load-load pair standard can also be used but not a short-short pair standard as it leads to a singularity when solving the equations. To test the method, a 10-dB attenuator was measured using a G-band on-wafer probe system. The results showed that the correction using the new error model provide improvement by almost 1-dB (i.e., 10%) compared with the conventional SOLT method.

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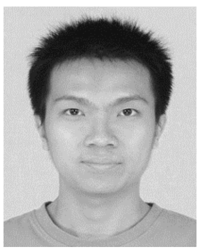

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